WINDSOR CONFERENCE
Rethinking comfort
12th - 15th April 2018

Seeing is Believing, or is it? An assessment of the influence of interior finish characteristics on thermal comfort perception at a University campus in a temperate climate

Jansen Foo[1] and Anna Mavrogianni[1]

[1] UCL Institute for Environmental Design and Engineering (IEDE), The Bartlett School of Environment, Energy and Resources (BSEER), The Bartlett Faculty of the Built Environment, University College London (UCL)

Abstract: Being a 'condition of mind', thermal comfort can be considered to be both a physiological and psychological response. Research shows that other than the physiological factors which are well established in prevailing thermal comfort standards, behavioural and psychological factors equally affect how humans adapt to the thermal conditions of their environment. Human response to thermal conditions is often based on predispositions associated with their perception and expectations of the physical environment. This paper examined the impact of interior finish characteristics on thermal comfort perception in learning spaces by analysing thermal comfort perceptions of students across 48 lecture theatres surveyed during the winter and spring season between 2012 and 2015 in University College London. A taxonomy of interior finish characteristics was first developed to guide the classification of the lecture theatres into different groups for statistical analysis. Results from hypothesis testing found small yet statistically significant differences in thermal comfort as a function of the colour hues (Δ = 0.1) as well as the perceived naturalness (Δ = 0.06) of interior finish characteristics. The findings of this study may have potential implications for the interior design of low carbon and healthy buildings that aim to minimize energy used for space heating whilst maintaining high indoor thermal comfort.

Keywords: Thermal comfort, Interior finish characteristics, Lecture theatres, Statistical hypothesis tests, Psychological thermal comfort adaptation

1. Introduction

The notion that thermal comfort is a condition of mind that expresses satisfaction with the thermal environment is widely accepted in the current research paradigm (ASHRAE 2013). Based on extensive research of how physical and personal variables, such as air and radiant temperature, air velocity, relative humidity, metabolic rate and clothing levels, affect human thermal comfort, existing codes and standards such as the American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE) Standard 55 (ASHRAE 2013) and the ISO 7730 Standard (ISO 2005) prescribe a precise band of universally applicable thermal comfort temperatures and conditions (Hejis et al. 1998). These standards are based on the heat balance model, which describes how the human thermoregulatory system maintains optimum body temperature through heat production and exchange with the environment (Fanger 1970; ASHRAE 2013). Such universal application often requires the introduction of mechanical heating or cooling systems in order to achieve indoor thermal comfort (Chappells et al. 2005). This is unsurprising as the aim of traditional thermal comfort research was to guide the design of engineered systems (Healey et al. 2012). In the face of current challenges posed by a warming climate, however, the way we design and manage buildings requires a rethink in order to simultaneously mitigate and adapt to climate change whilst enhancing people's health and wellbeing.

A large and growing body of research indicates that not only *physical* and *physiological* factors, but also *sociocultural* and *psychological* factors may affect thermal comfort (Hejis et al. 1998; Parsons 2003). The adaptive thermal comfort model, which is mainly applied to free running buildings, recognises that past thermal experiences, cognitive expectations, cultural background and other individual factors can appreciably influence occupant thermal comfort satisfaction (Brager & de Dear 1998; Humphreys et al. 2016). Studies have shown that by incorporating occupant control, the adaptive model enables thermal comfort to be achieved over a wider range of temperatures (Brager et al. 2004) as the positive emotion conjured by having control over a space is comforting itself (Cohen et al. 1986). The lesson drawn from such research is that thermal comfort is a dynamic phenomenon that encompasses psychological, social and cultural factors.

1.1. Seeing is believing, or is it?

The way people perceive and respond to the conditions of their immediate physical environment is often based on past experiences and accumulated knowledge stored in their memory (Gregory 1970). Those experiences shape a person's expectations. It is shown that emotions associated with sensations that one experienced in a physical space would form part of one's personal memory (Poppelreuter 2012), and the physical design characteristics of a space have been shown to impact on people's mental state. Architects and designers have long capitalized on place related memories by using colour, material, texture, architectural form and other design elements in attempts to evoke spatial experiences, which in turn induce varying emotions and moods (Holl et al. 2006; Pallasmaa 2005; Ritterfeld & Cupchik 1996; Roessler 2012). For example, lower ceiling heights may create a more intimate and relaxing mood compared to higher ceilings, which are perceived as indicative of formal spaces (Alexander et al. 1977). Similarly, shiny surfaces are found to be more stimulating compared to matte surfaces, which are perceived to be more calming (Augustin 2009).

Being a 'condition of mind', thermal comfort could be seen as a both physiological and psychological response (Rohles 2007). However, the relationship between the physical design features of indoor spaces and perceived thermal comfort is seldom explored in the current research paradigm. This knowledge gap is partly addressed by this study, which explores the relationship between interior finish characteristics and thermal comfort in learning environments. To achieve this, self-reported thermal comfort responses of students across 48 lecture theatres surveyed during winter and spring months between 2012 and 2015 in University College London (UCL) were analysed in relation to the interior finish characteristics of the surveyed spaces.

2. Psychological factors in thermal comfort

It is widely acknowledged that physical factors, such as air temperature, mean radiant temperature, air velocity, relative humidity, and personal factors, such as clothing level and metabolic rate, contribute to the heat balance of a human body and influence thermal comfort (de Dear et al. 2013). Existing literature shows that to achieve thermal comfort, human adaptive behavioural, physiological and psychological processes also come into play, of which the impact of psychological processes are least explored. People perceive their physical environment differently and their responses to a physical stimulus or particular situation depend on accumulated knowledge stored within their memory (Gregory 1970). Psychological factors, such as experiences, expectations, naturalness and perceived control can influence the thermal perception and evaluation of a space (Rajapaksha 2017; Nikolopoulou & Steemers 2003; de Dear et al. 1997; Auliciems 1981).

Past experiences shape people's expectations of their thermal environment, which in turn affect how they respond to thermal environmental conditions (Willey 1987). An individual's adaptation level and choice of action to cope with changes in the thermal environment depends on past exposures, thermal history and experiences (Wohlwill 1974). Removing clothing and consuming a cold drink on a hot day or putting on extra clothing before getting out of a building to get into the car on a cold winter day are all decisions made according to the memories and understanding of past experiences. Those experiences could be the unpleasant feelings of warm and cold discomfort on a hot and cold day respectively.

Expectation predisposes people to perceive their thermal environment by what they think it should be like rather than what it really is (Nikolopoulou et al. 2001). Often, this is influenced by past thermal experiences (Auliciems 1981). The predisposition that people have of how they feel the environment should be like influences their thermal perception ultimately (Nikolopoulou & Steemers 2003). For example, people from warm climates would be more inclined to expect variations in thermal conditions in a free running building and more prepared to accept higher indoor temperatures (Fanger & Toftum 2002). Such expectations predispose people psychologically on the thermal sensation they think they would feel once they enter those spaces, thus prompting subsequent actions to cope with the anticipated thermal conditions (de Dear et al. 1991).

Naturalness of indoor spaces is defined as inclusion of natural elements or the replication of processes and places of nature (e.g. flowing streams, forests, etc.). The degree of naturalness of an environment has been found to impact the thermal perception of users (Nikolopoulou et al. 1999; Hirashima et al. 2016; Rajapaksha 2017). In particular, it has been shown that people are more likely to tolerate a wider range of thermal conditions in environments with a higher degree of perceived naturalness (Eliasson et al. 2007).

The availability of either actual or perceived occupant environmental *control* has also been found to increase thermal satisfaction in both air conditioned and free running buildings (Nicol & Humphreys 2002; Brager et al. 2004; Fountain & Brager & de Dear 1996; Mors et al. 2011; de Dear et al. 2013).

2.1. Physical design characteristics of a space and their impact on thermal comfort

There is currently limited knowledge as to how much the physical design characteristics of a space impact thermal comfort perception. Key findings of previous studies on the effects of physical design characteristics on thermal comfort perception are summarized in Table 1. The studies indicate that the physical design characteristics of a space such as interior design, colour hues and presence of natural elements like plants may potentially affect people's perceived thermal comfort. However, the majority of these studies were conducted in controlled laboratory conditions; there is a lack of larger scale studies in real world settings that capture a wide range of interior finish characteristics.

Table 1. Summary of findings from previous studies

Study	Study indicated that psychological factors may have impacted results	Key findings
Rohles et al. (1976)	Yes	Subjects felt warmer in a room finished with natural materials, timber wall panels, red textured carpet and 'warm' lighting.
Ohta et al. (2007)	Yes	Subjects had higher body temperature and felt more thermally comfortable and relaxed in a room with natural elements, such as timber wall panels and Japanese paper.
Fanger (1977)	Neutral	Subjects prefer a lower ambient temperature (0·4°C) under red lighting compared to blue lighting.
Huebner et al. (2016)	Yes	Results support the hue-heat hypothesis as subjects felt more thermally comfortable and warmer in 'warm' light conditions.
Berry (1961)	Neutral	Subjects did not feel more thermally comfortable under "warm" lighting but perceived the coloured lights they experienced according to the hue-heat hypothesis
Bennet (1972)	Neutral	Results on whether wearing coloured goggles have an effect on judgement of temperature was ambiguous. The author speculated that the light effect of the goggles may have confounded the results.
Kobayashi et al. (1992)	Yes	Subjects felt warmer under lower colour temperature (warm-coloured) lights.
Mangone et al. (2014)	Yes	Presence of plants in the space contributed to subjects feeling more thermally comfortable and relaxed.
Qin et al. (2014)	Yes	Subjects were more thermally comfortable, relaxed and showed more satisfaction with the physical environment in spaces with plants.

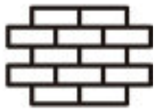
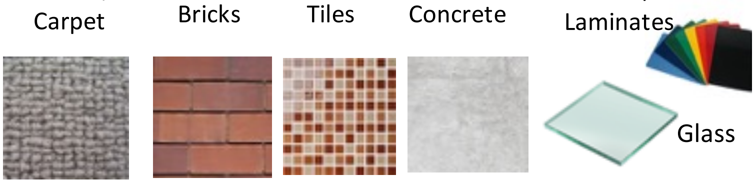
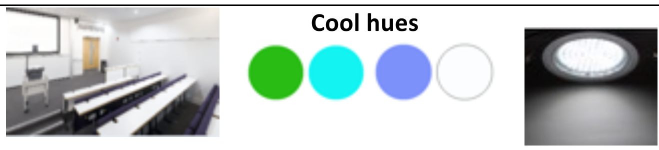
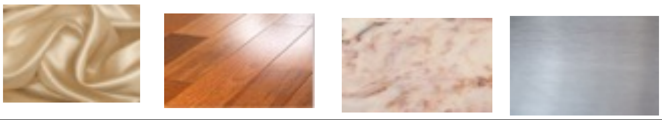
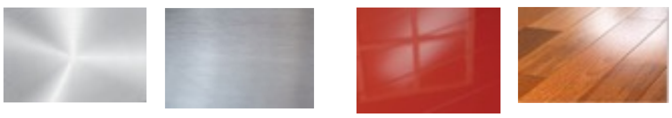
3. Methods

An existing dataset comprising questionnaire surveys of occupant thermal comfort in UCL lecture theatres was used for this study. A taxonomy of interior finish characteristics developed based on factors identified during the literature review was used to organize the surveyed lectures theatres into different groups. Next, statistical analysis and hypothesis testing were performed on the thermal comfort dataset to determine if significant differences exist between lecture theatres with different interior finish characteristics.

3.1. Taxonomy of interior finishes

To guide the classification of UCL lecture theatres for statistical testing, a taxonomy of interior finish characteristics was proposed. Building on previous studies (Berry 1961; Rohles et al. 1976; Fanger 1970; Fanger 1973; Fanger et al. 1977; Kobayashi et al. 1992; Nikolopoulou et al. 1999; Candas et al. 2005; Ohta et al. 2007; Mangone et al. 2014; Qin et al. 2014; Hirashima et al. 2016; Huebner et al. 2016; Rajapaksha 2017), the interior finish characteristics include: i) naturalness, ii) colour hue, iii) texture and iv) sheen. Table 2 illustrates the proposed taxonomy.

Table 2. Taxonomy of interior finish characteristics

Characteristic	Grouping (with examples shown)	Relevant studies
 Naturalness	**Natural materials** 	Rohles et al. (1976); Ohta et al. (2007); Mangone et al. (2014); Qin et al. (2014); Nikolopoulou et al. (1999); Hirashima et al. (2016); Rajapaksha (2017)
	Heavily processed human-made materials Fabrics/ Carpet, Bricks, Tiles, Concrete, Plastics/ Laminates, Glass 	
 Colour hue	**Warm hues**  Warm lighting	Fanger et al. (1977); Berry (1961); Candas et al. (2005); Huebner et al. (2016); Kobayashi et al. (1992)
	Cool hues  Cool lighting	
 Texture	**Smooth texture** 	Rohles et al. (1976); Ohta et al. (2007);
	Rough texture 	
 Sheen	**Gloss** 	Rohles et al. (1976); Ohta et al. (2007); Fanger (1970); Fanger (1973)
	Matte 	

3.2. Data collection process and sampling method

The surveys were conducted by MSc Environmental Design and Engineering students at the UCL Institute for Environmental Design and Engineering, The Bartlett, in the context of the Methods of Environmental Analysis module coursework during winter (October to

November) and spring (January to March) months between 2012 and 2015. Table 3 shows a summary of the data collection statistics. There is a total of 52 different lecture theatres in the dataset, however, not all lecture theatres were included in the data collection exercise every year. A convenience sampling method was adopted where the selection of subjects was not governed by any specific criteria. Lecturers were contacted in advance in order to obtain their agreement prior to conducting the surveys. Each questionnaire survey was conducted at different days and times in each lecture theatre during the course of an ongoing lecture (typically ranging between 1 and 3 hours). The average response rate was 74% across lecture theatres and survey periods.

Table 3. Summary of data collection statistics

Year	Total number of lecture theatres	Total capacity of all lecture theatres	Total number of students present in lecture theatres	Total number of responses	Average response rate	Date range of data collection	Average duration of survey
2012	38	4081	2223	1756	79%	3 Feb – 22 Feb	1.8 hours
2013	36	3568	1919	1434	75%	28 Jan – 21 Feb	2.0 hours
2014 (1st half) (1H)	41	4645	2216	1810	82%	10 Feb – 10 Mar	1.8 hours
2014 (2nd half) (2H)	46	5255	2907	2146	74%	27 Oct – 30 Nov	1.8 hours
2015	37	4285	3940	2599	80%	28 Oct – 26 Nov	1.7 hours
Total			13205	9745	74%		

Figure 1 shows the locations of the 52 lecture theatres. Data from 4 lecture theatres in the UCL Bentham house* were not considered in this study as the lecture theatres were undergoing refurbishment works and could not be accessed for physical verifications of their interior finishes.

* Bentham B01 Main LT; Bentham B11 Seminar Room 4; Bentham B31 Denys Holland LT; Bentham SB01 Seminar Room 3

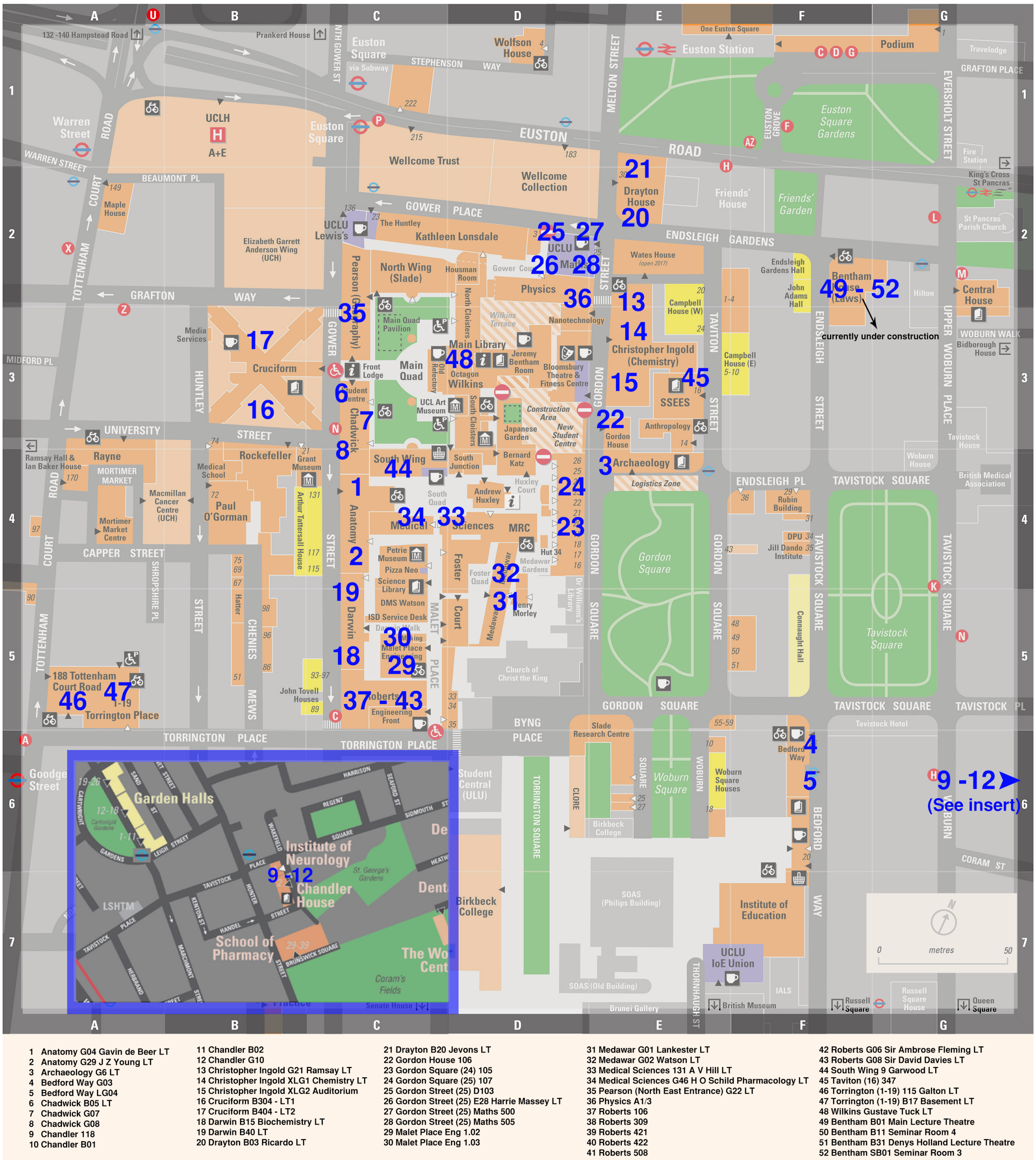


Figure 1. Locations of lecture theatres across UCL campus

Figure 2 shows examples of the interior finish characteristics of the 48 lecture theatres involved in this study.

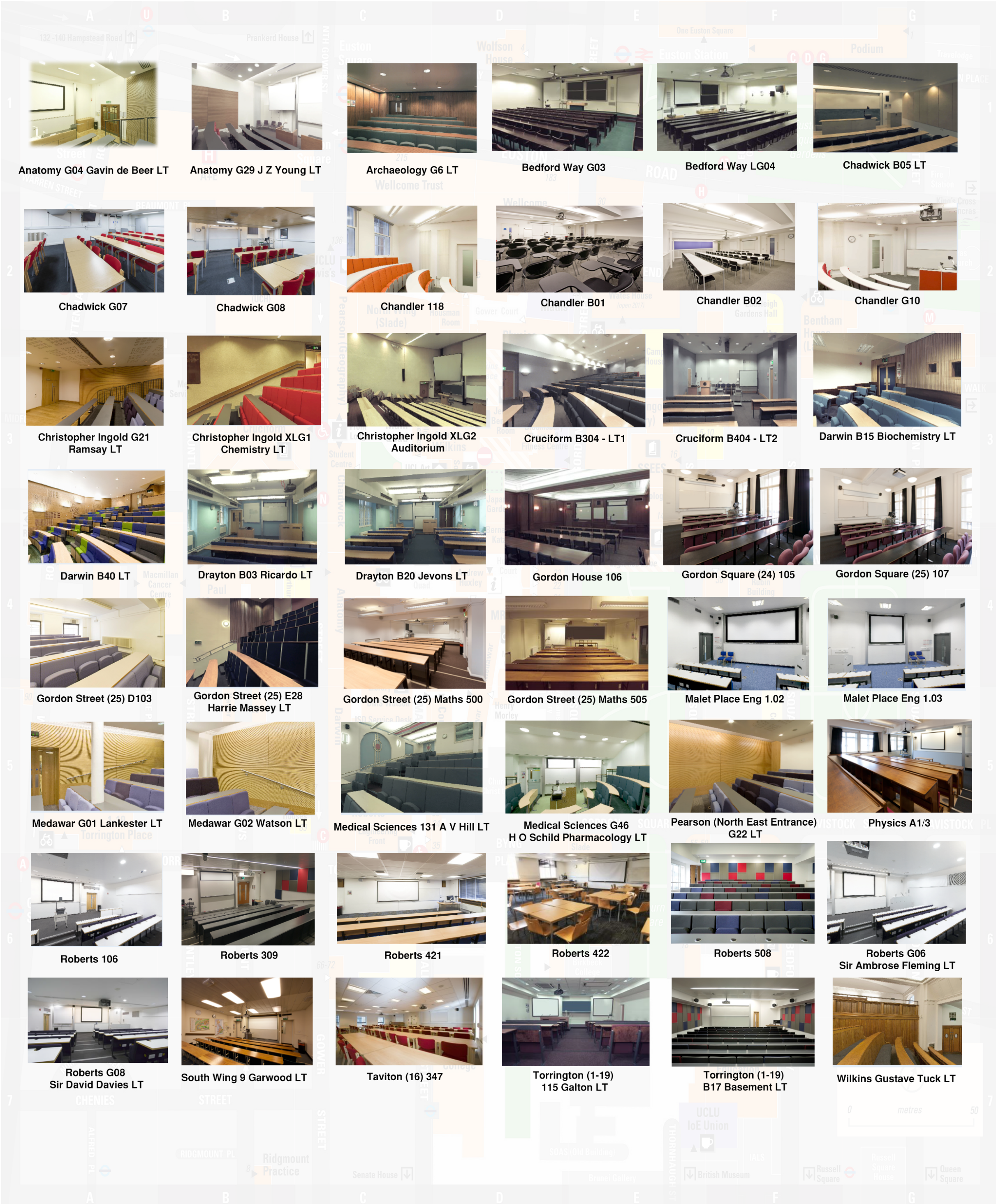


Figure 2. Examples of interior finish characteristics of lecture theatres

The lecture theatre surveys consisted of two components:

- HOBO data loggers were used to measure dry bulb temperature and relative humidity (Onset HOBO U12-02 with accuracy for temperature measurements ± 0.35 °C and ± 25% for relative humidity) at varying intervals (5 to 10 minutes) in the lecture theatres throughout the duration of an ongoing lecture.

- Self-administered questionnaires were handed out to all students present in each lecture theatre. They contained a series of questions on how the students rated the following parameters in the specific lecture theatre:
    i) thermal comfort (using ASHRAE scale 1 = cold to 7 = hot);
    ii) visual comfort;
    iii) acoustic comfort;
    iv) indoor air quality;
    v) ergonomics of furniture;
    vi) ability to concentrate;
    vii) availability of thermal set point control;
    viii) basic design;
    ix) accessibility;
    x) maintenance;
    xi) quality of facilities such as electrical sockets, internet access etc.

The students were also invited to indicate their seating position in the questionnaire after completing the survey.

3.2. Classification of lecture theatres

For the purpose of statistical analysis, the lecture theatres were grouped according to their interior characteristics (naturalness of materials; colour hue; texture; sheen). A lecture theatre was assigned a particular characteristic if that characteristic applied to the largest proportion of its surface areas. The lecture theatres were grouped as follows:

1) **Naturalness**
   Group 1: Lecture theatres with interior finish of natural materials, such as timber, stone etc.
   Group 2: Lecture theatres with heavily processed human-made materials, such as concrete, plastic laminates etc.

Darwin B40 with natural timber interior finish

Roberts 106 with heavily-processed materials

Figure 3. Examples of different material interior finishes

2) **Colour hue**
   Group 1: Lecture theatres with interior surface finishes of warm hue colours.
   Group 2: Lecture theatres with interior surface finishes of cool hue colours.

Darwin B40 with mainly warm hues

Roberts 106 with cool hues

Figure 4. Examples of different interior colour hues

3) **Texture**
Group 1: Lecture theatres with interior surface finishes of smooth texture.
Group 2: Lecture theatres with interior surface finishes of rough texture.

Christopher Ingold building G21 Ramsay LT with smooth parquet floor and vinyl laminate table tops

Christopher Ingold building XLG1 Chemistry LT with carpeted floor, fabric seats and textured wall finish

Figure 5. Examples of different interior textures

4) **Sheen**
Group 1: Lecture theatres with gloss interior surface finishes.
Group 2: Lecture theatres with matte interior surface finishes.

Wilkins Gustave Tuck LT with glossy panels and table tops

Anatomy G29 J Z Young LT with matte interior

Figure 6. Examples of different degree of sheen

3.3. Statistical analysis and hypothesis testing

The quantitative data collected from the surveys were statistically analysed using Microsoft Excel 2016 installed with Analysis ToolPak add-in (Microsoft 2017). Two stages of statistical hypothesis testing through Student's t-tests and single factor Analysis of Variance (ANOVA) tests were carried out to examine potential relationships between thermal comfort levels and interior finish characteristics.

For the first stage, a series of unpaired, two tailed Student's t-tests were performed for the following pairs of hypotheses (null hypothesis, H_0 and alternative hypothesis H_1):

1) **Naturalness**

   $\boldsymbol{H_0}$**:** There is no difference in occupant thermal comfort levels between lecture theatres with interiors with natural materials and lecture theatres with heavily processed human-made materials.

   $\boldsymbol{H_1}$**:** There is a difference in occupant thermal comfort levels between lecture theatres with interiors with natural materials and Lecture theatres with heavily processed human-made materials.

2) **Colour hues**

   $\boldsymbol{H_0}$**:** There is no difference in occupant thermal comfort levels between lecture theatres with interiors of warm hues and lecture theatres with interiors of cool hues.

   $\boldsymbol{H_1}$**:** There is a difference in occupant thermal comfort levels between lecture theatres with interiors of warm hues and lecture theatres with interiors of cool hues.

3) **Texture**

   $\boldsymbol{H_0}$**:** There is no difference in occupant thermal comfort levels between lecture theatres with interiors with smooth textures and lecture theatres with interiors with rough textures.

   $\boldsymbol{H_1}$**:** There is a difference in occupant thermal comfort levels between lecture theatres with interiors with smooth textures and lecture theatres with interiors with rough textures.

4) **Sheen**

   $\boldsymbol{H_0}$**:** There is no difference in occupant thermal comfort levels between lecture theatres with interiors with gloss surface finish and lecture theatres with matte surface finish.

   $\boldsymbol{H_1}$**:** There is a difference in occupant thermal comfort levels between lecture theatres with interiors with gloss surface finish and lecture theatres with matte surface finish.

The aim of the statistical tests was to explore any statistically significant differences in thermal comfort between the groups of different interior finish characteristics. The significance level for the tests was set at 0.05 or 5%.

For the second stage, the interior finish characteristics with t-test results for which the null hypothesis was rejected were further analysed using single factor ANOVA tests. In these tests, the lecture theatres were reclassified into multiple groups of interior finish characteristics.

As the lecture theatre surveys were carried out with the students seated and facing the front of the lecture theatre where the lecturer and projector screen are, the interior surfaces that are predominantly in the students' effective visual field would be the walls of the lecture theatre and the table tops. Figure 7 shows an example of a lecture theatre visual field. As such, the finish characteristics of the walls and table tops may influence the thermal comfort perception of the students. The ANOVA tests would explore whether there are any significant differences between thermal comfort perception and different combinations of surface finish characteristics of the lecture theatre walls and table tops. For the naturalness of interior finish materials, the lecture theatres were classified into the following four groups for the ANOVA test:

i) Natural walls / Natural table tops
ii) Natural walls / Heavily processed human-made table tops
iii) Heavily processed human-made walls / Natural table tops
iv) Heavily processed human-made walls / Heavily processed human-made table tops

The null hypothesis (H_0) and alternative hypothesis (H_1) are:

***H*$_0$**: There is no difference in occupant thermal comfort levels in lecture theatres with different combinations of natural and heavily processed wall and table top materials.

***H*$_1$**: There is a difference in occupant thermal comfort levels in lecture theatres with different combinations of natural and heavily processed wall and table top materials.

For colour hue, the lecture theatres were classified into separate groups with the following interior finish characteristics:

i) Warm coloured wall / Warm coloured table top
ii) Warm coloured wall / Cool coloured table top
iii) Cool coloured wall / Warm coloured table top
iv) Cool coloured wall / Cool coloured table top

The null hypothesis (H_0) and alternative hypothesis (H_1) are:

***H*$_0$:** There is no difference in occupant thermal comfort levels in lecture theatres with different combinations of wall and table top colours.

***H*$_1$:** There is a difference in occupant thermal comfort levels in lecture theatres with different combinations of wall and table top colours.

Figure 7. Example of visual field of a student seated in a LT

4. Results

4.1. T-test results

The results of the two-tailed Student's t-tests for the hypotheses outlined above for naturalness, colour hue, texture and sheen are presented below.

1) Naturalness

Table 4 shows the two-tailed t-test results on thermal comfort perception between lecture theatres with natural materials and heavily processed human-made materials.

Table 4. t-test results for thermal comfort and naturalness of materials

Grouping	Number of votes (N)	Mean thermal comfort vote	Std Dev	df	$t_{statistic}$	p	Reject null hypothesis?	Effect size
Natural materials	**4186**	**4.109**	**1.194**	**9761**	**2.378**	**0.0174**	**Yes (p≤0.05)**	**0.05**
Heavily processed human-made materials	**5577**	**4.052**	**1.179**					

H₀: There is no difference in occupant thermal comfort levels between Lecture theatres with interiors with natural materials and lecture theatres with heavily processed human-made materials.
H₁: There is a difference in occupant thermal comfort levels between lecture theatres with interiors with natural materials and Lecture theatres with heavily processed human-made materials.

From the results, the null hypothesis can be rejected at 5% significance level. Hence, there is a statistically significant, albeit very small (Δ = 0.06), difference between occupant thermal comfort in lecture theatres with natural material finish and lecture theatres with heavily processed human-made material finish.

2) Colour hue

Table 5 shows the two-tailed t-test results on thermal comfort perception between lecture theatres with cool hues and warm hues.

Table 5. t-test results for thermal comfort and colour hues

Grouping	Number of votes (N)	Mean thermal comfort vote	Std Dev	df	$t_{statistic}$	p	Reject null hypothesis?	Effect size
Cool hues	**7211**	**4.053**	**1.178**	**9761**	**-3.336**	**0.000854**	**Yes (p≤0.05)**	**0.08**
Warm hues	**2552**	**4.144**	**1.214**					

H₀: There is no difference in occupant thermal comfort levels between lecture theatres with interiors of warm hues and lecture theatres with interiors of cool hues.
H₁: There is a difference in occupant thermal comfort levels between lecture theatres with interiors of warm hues and lecture theatres with interiors of cool hues.

From the results, the null hypothesis can be rejected at the 5% significance level. Hence, there is a statistically significant small difference (Δ = 0.1) between occupant thermal comfort in lecture theatres with cool hues and lecture theatres with warm hues.

3) Texture

Table 6 shows the two-tailed t-test results on thermal comfort perception between lecture theatres with smooth and rough textures.

Table 6. t-test results for thermal comfort and different textures

Grouping	Number of votes (N)	Mean thermal comfort vote	Std Dev	df	$t_{statistic}$	p	Reject null hypothesis?
Smooth texture	**3628**	**4.075**	**1.202**	**9761**	**-0.074**	**0.941**	**No (p>0.05)**
Rough texture	**6135**	**4.077**	**1.164**				

H₀: There is no difference in occupant thermal comfort levels between lecture theatres with interiors with smooth textures and lecture theatres with interiors with rough textures.
H₁: There is a difference in occupant thermal comfort levels between lecture theatres with interiors with smooth textures and lecture theatres with interiors with rough textures.

From the results, the null hypothesis cannot be rejected at the 5% significance level. For the examined sample, the difference in user thermal comfort in lecture theatres with smooth textured interior finishes and those with rough textured interior finishes characteristics were negligible and not statistically significant.

4) Sheen

Table 7 shows the two-tailed t-test results on thermal comfort perception between lecture theatres with gloss and matte finish.

Table 7. t-test results for thermal comfort and different interior sheen

Grouping	Number of votes (N)	Mean thermal comfort vote	Std Dev	df	$t_{statistic}$	p	Reject null hypothesis?
Gloss	**2050**	**4.067**	**1.204**	**9761**	**0.411**	**0.681**	**No (p>0.05)**
Matte	**7713**	**4.079**	**1.184**				

***H_0*: There is no difference in occupant thermal comfort levels between lecture theatres with interiors with gloss surface finish and lecture theatres with matte surface finish.**

***H_1*: There is a difference in occupant thermal comfort levels between lecture theatres with interiors with gloss surface finish and lecture theatres with matte surface finish.**

From the results, the null hypothesis cannot be rejected at the 5% significance level. In other words, the observed (small) difference in user thermal comfort in lecture theatres with gloss interior finish characteristics and lecture theatres with matte interior finish characteristics may be due to chance.

4.2. ANOVA test results

Based on the results of the t-tests in the section above, single factor ANOVA tests were carried out to further explore whether there are any significant differences between thermal comfort perception and the various degrees of *naturalness* and *colour hue* of the lecture theatre walls and table tops. The results of the single factor ANOVA tests are presented below.

1) Naturalness

The significance level for the test is set at 0.05 or 5%. Table 8 shows the results of the ANOVA test for the varying degrees of naturalness.

Table 8. ANOVA table for thermal comfort and different interior material characteristics

SUMMARY						
Groups	*Count*	*Sum*	*Average thermal comfort vote*	*Variance*		
Natural wall / Natural table top	**919**	**3569**	**3.88**	**1.26**		
Natural wall / Heavily processed table top	**1356**	**5417**	**3.99**	**1.60**		
Heavily processed wall / Natural table top	**3135**	**12917**	**4.12**	**1.40**		
Heavily processed wall / Heavily processed table top	**3573**	**14583**	**4.08**	**1.37**		
ANOVA*						
Source of Variation	*SS*	*df*	*MS*	*F*	*p-value*	*F critical*
Between Groups	**47.36**	**3**	**15.79**	**11.28**	**2.33×10^{-7}**	**2.61**
Within Groups	**12610.47**	**8979**	**1.40**			
Total	**12657.83**	**8982**				

* SS: sum of squares; df: degree of freedom; MS: mean square; F: F statistic

From the ANOVA results, the null hypothesis can be rejected at the 5% significance level. Hence, there is a significant difference in occupant thermal comfort in lecture theatres with different combinations of wall and table top materials.

2) Colour hue

Table 9 shows the results of the ANOVA test for colour hue.

Table 9. ANOVA table for thermal comfort and different interior colours

SUMMARY						
Groups	*Count*	*Sum*	*Average thermal comfort vote*	*Variance*		
Warm coloured wall / Warm coloured table top	**1345**	**5406**	**4.02**	**1.45**		
Warm coloured wall / Cool coloured table top	**1402**	**5431**	**3.87**	**1.42**		
Cool coloured wall / Warm coloured table top	**3267**	**13418**	**4.11**	**1.37**		
Cool coloured wall / Cool coloured table top	**2942**	**12111**	**4.12**	**1.41**		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*p-value*	*F critical*
Between Groups	**67.53**	**3**	**22.51**	**16.07**	**2.13×10^{-10}**	**2.61**
Within Groups	**12561.67**	**8952**	**1.40**			
Total	**12629.1992**	**8955**				

From results, the null hypothesis can be rejected at the 5% significance level as p-value is less than 0.05. Hence, there is significant difference between occupant thermal comfort in lecture theatres with different combinations of wall and table top colours.

4.3. Distribution of temperature and relative humidity across all lecture theatres

Figures 8 and 9 demonstrate the distribution of the average, minimum and maximum temperatures; and relative humidity (RH) of the lecture theatres (from 2015 to 2012) examined, respectively. Whilst temperature distributions vary across lecture theatres, such differences are not statistically significant in their majority. The only lecture theatre for which there is a significant difference compared to other lecture theatres is Chandler B02.

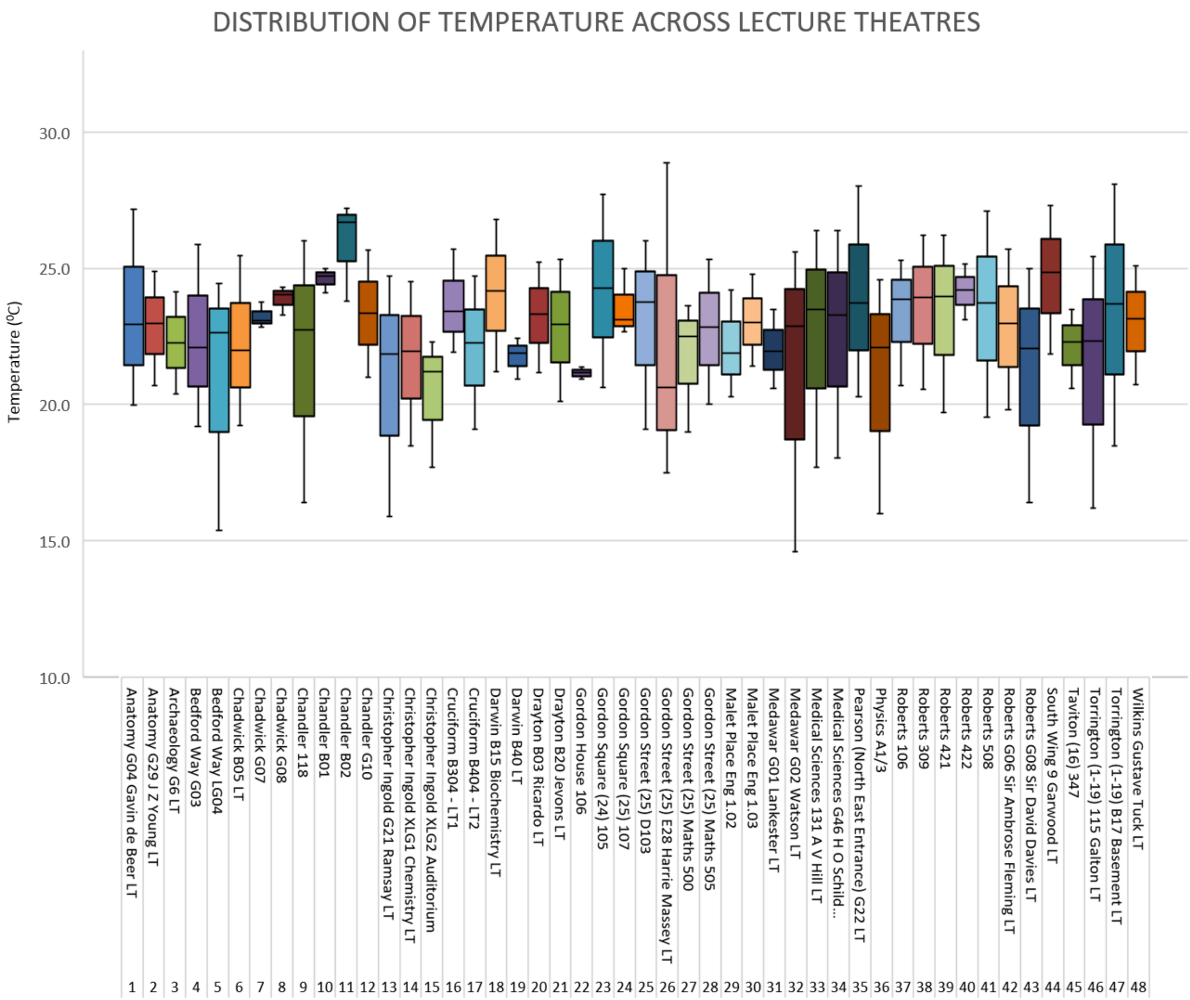


Figure 8. Box plot of temperature distribution across lecture theatres

Unlike the distribution of temperature, the spread of RH across the lecture theatres is much wider. The significant differences between the RH of the lecture theatres may affect the student’s thermal comfort levels in the different lecture theatres.

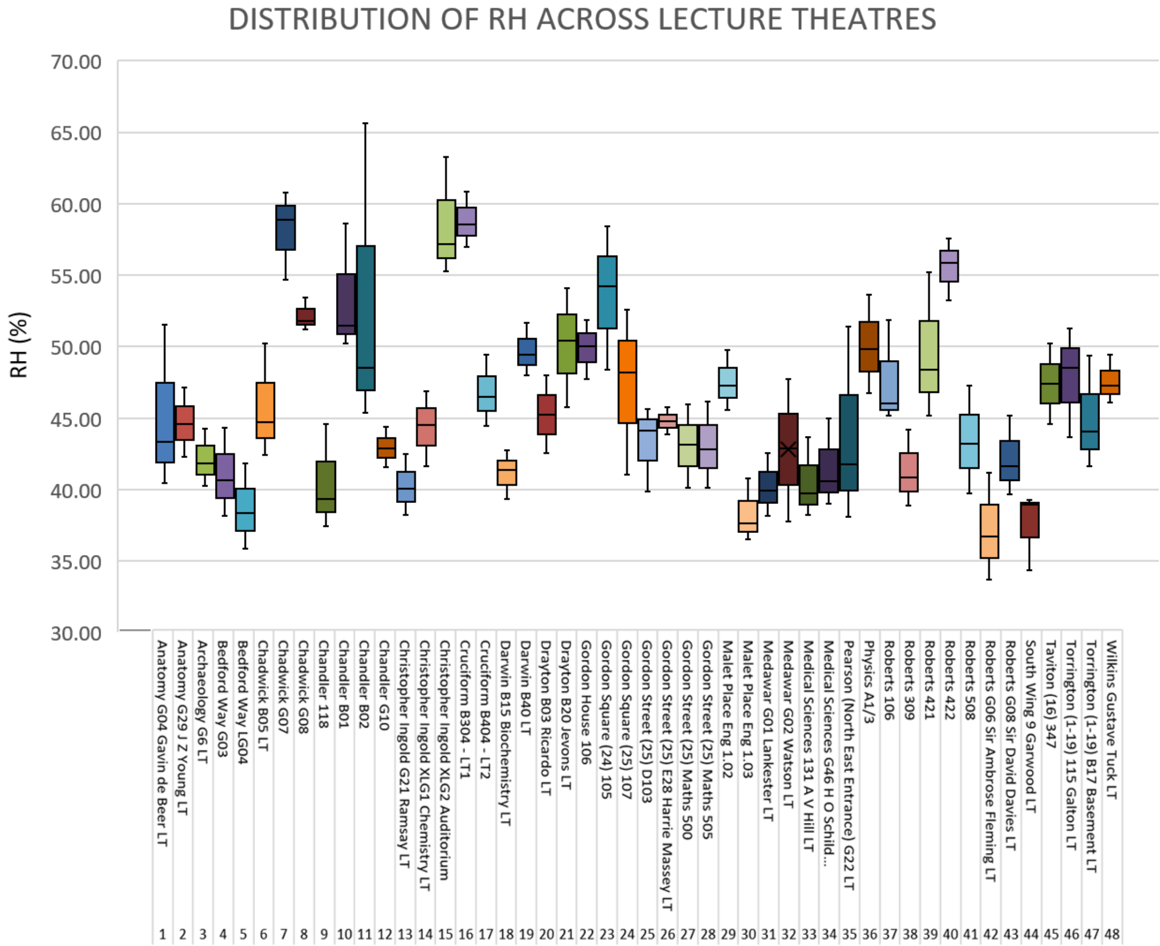


Figure 9. Box plot of RH distribution across lecture theatres

5. Discussion

Statistical hypothesis testing using t-tests was carried out to examine the impact of interior finish characteristics, such as naturalness of materials, colour hue, texture and sheen on thermal comfort perception. A potentially interesting relationship was found between thermal comfort perception with the interior finish characteristics of colour hue and degree of naturalness of materials. Further analysis through ANOVA tests affirmed the potential relationship within the existing dataset although the observed differences are small and the direction of the relationship still slightly unclear. This finding is, nevertheless, in line with earlier studies (Rohles et al. 1976; Ohta et al. 2007; Huebner et al. 2016; Qin et al. 2014), which have suggested that interior finish characteristics, such as naturalness of materials and colour hue, may have potential psychological effects on occupant thermal comfort perception.

Interestingly, further statistical analysis through ANOVA tests also found statistically significant differences and a potential relationship between thermal comfort perception and different combinations of lecture theatre wall and table finish characteristics. However, a closer examination of the average thermal comfort votes for the respective combinations produced contradictory observations, which are in contrast with some of the studies reviewed. For example, in line with the 'hue-heat' hypothesis, one would expect lecture theatres with both warm coloured walls and warm coloured table tops to have a higher average occupant thermal comfort vote closer to the warm side of the thermal sensation scale. However, the results (see Table 9) show that the average thermal comfort vote for lecture theatres with warm coloured walls and table tops was only 4.02 compared to an average of 4.12 for lecture theatres with cool-coloured walls and table tops. Similarly, in the ANOVA test for degree of naturalness of materials, one would expect lecture theatres with the combination of both natural wall and table top materials to have the highest average thermal comfort votes. It was those with heavily processed walls and natural table tops that had the highest average, however.

It is also worth noting that rejecting the null hypothesis does not necessarily prove that there is a causal relationship between thermal comfort and the above factors. Multiple confounding factors may have contributed to the observations above. It could be that the lecture theatres with cool coloured walls and table tops, and heavily processed walls and natural table tops may have lighting fixtures of lower colour temperatures or 'warm' lighting compared to the others; or maybe the environmental controls of those lecture theatres are located in more visible locations which allowed the students to adjust the set point temperatures to their preferred levels etc.

Also, contrary to some studies (Fanger 1973; Rohles et al. 1976; Ohta et al. 2007), the statistical tests on the interior finish characteristics of texture and sheen did not show any statistical significant difference or any potential relationship with thermal comfort within the dataset used. The results, however, do not dismiss any potential relationship between those characteristics and thermal comfort even though they do not show up in the research dataset as once again, there may have been confounding factors.

5.1. Limitations of study and further research

It is worth noting that there may be confounding factors that may have affected the students' thermal sensation and satisfaction and ultimately the thermal comfort votes collected. These factors may be behavioural, physiological and psychological in nature (de Dear et al. 2013; Nicol & Humphreys 2002; Yao et al. 2009; Brager & de Dear 1998; de Dear, R.J. & Leow, K. & Foo, S. 1991).

First, the duration of the lectures differed. They generally lasted between 1 to 3 hours. This meant that students in the short 1-hour lectures may not have had time to acclimatise to the thermal conditions in the lecture theatre and may have responded differently to those whom were in another lecture theatre for a 3-hour lecture, even if the thermal conditions may have been similar. Some students may have changed their clothing level several times during the survey and this may have affected the results.

Second, although the dataset comprises of a good range of lecture theatres with varying interior finish characteristics and a large sample of student respondents, the data collection and surveys were conducted over multiple years with different external weather conditions.

Additionally, the survey did not collect information on factors such as the sociocultural background and acclimatisation levels of the students, which are shown to affect thermal comfort perceptions (Brager & de Dear 1998). It is possible that some of the lecture theatre survey sessions comprised of a larger proportion of international students with different expectations from their thermal environment, e.g. potentially acclimatised to higher indoor temperatures (Fanger & Toftum 2002) compared to their counterparts from temperate climates.

Furthermore, some students may have travelled out of the UK to a different climatic region before the questionnaire survey took place. They may have acclimatised to the local thermal conditions and this might have affected their thermal comfort levels and sensations during the survey (de Dear et al. 1997). Another significant confounding factor may be colour temperature of the lighting used in the lecture theatres, which was not covered in this study.

Despite the limitations outlined above, results from this study have indicated that an interesting relationship may potentially exist between thermal comfort perception and interior finish characteristics, such as degree of naturalness of materials and colour hue. In the UK, a large proportion of national energy use is attributed to maintaining indoor thermal comfort standards through thermal conditioning (Knapp 2015). Current practices are not in line with existing energy policies and regulations. Instead of following the conventional way of tackling thermal comfort issues through mechanical means to keep thermal conditions of buildings within a narrow band of acceptable conditions, the thermal comfort range could be larger, allowing occupants to adapt to their thermal environment (Brager & de Dear 1998; Vine 1986). Further studies on the topic may open up a wealth of possibilities in human thermal comfort understanding where comfort can be improved through evidence based and creative interior design solutions, such as using natural materials and colours, and with minimal or no mechanical means, thus improving people’s sensory experiences of indoor spaces whilst reducing the carbon footprint of buildings.

6. Conclusions

This exploratory study set out to investigate the impact of interior finish characteristics on thermal comfort perception in learning spaces of higher education. A taxonomy of general interior finish characteristics was developed and was used to classify a large sample of lecture theatres across UCL into different groups for statistical analysis and hypothesis testing. From the statistical tests carried out on an existing dataset of thermal comfort surveys in these lecture theatres, it was found that there may exist a potentially interesting relationship between thermal comfort and the degree of naturalness and colour hue of the interior finishes of UCL lecture theatres. Further analysis also found that a relationship may exist between various combinations of wall and table top finish characteristics and thermal comfort. The findings above were in line with previous studies that have acknowledged the psychological effects that interior finish characteristics may have on occupant thermal comfort perception.

Being a mental state, thermal comfort perception is a subjective entity which is influenced by tangible physiological and behavioural elements, as well as intangible psychological elements, such as past experiences and current expectations. Similar to how architects and designers have often made use of intangible aspects of the environment such as form and materiality to create different experiences, this study focused on how intangible aspects of the environment may have a part to play in human thermal comfort perception. The findings of this study may potentially help to inform future explorations into the interesting relationship between thermal comfort and the materiality of spaces. From here, there are endless opportunities for further research focusing on interior finish materiality and thermal comfort. Future research should test the effects of specific interior finish characteristics under similar experimental conditions such as temperature, RH, clothing level, experiment duration etc. They should also take into account external weather and preferably be conducted in applied settings with a good mix of subjects from different sociocultural backgrounds. The interior finish characteristics should be varied an element at a time in order to dissociate their individual effects on thermal comfort. Such studies may be of practical interest to suppliers and manufacturers of construction materials as well as architects and designers for whom reducing building energy consumption as well as the health and wellbeing of occupants are increasingly becoming a priority. Also, academics and governments alike may be interested in the actual energy savings potential of addressing thermal comfort issues through interior space materiality rather than conventional mechanical means.

References

Alexander et al. 1977. *A pattern language : towns, buildings, construction*. New York : Oxford University Press.

ASHRAE. 2013. ANSI/ASHRAE Standard 55 - Thermal Environmental Conditions for Human Occupancy. Atlanta, ASHRAE Inc. pp. 3-6.

Augustin, S. 2009. *Place advantage : applied psychology for interior architecture.* Hoboken, N.J. : Wiley.

Auliciems, A. 1981. *Towards a psycho-physiological model of thermal perception.*

International Journal of Biometeorology, 25(2), pp.109-122.

Bennet, C.A. 1972. *What's so hot about red.* Human Factors,14, pp.149–154.

Berry, P.C. 1961. *Effect of colored illumination upon perceived temperature*. Journal of Applied Psychology, 45, pp.248–250.

Brager et al. 2004. *Operable windows, personal control and occupant comfort.* ASHRAE Transactions, 110 (2), pp. 17–35.

Brager, G. S. & de Dear, R. J. 1998. *Thermal adaptation in the built environment: a literature review.* Energy and Buildings, 27, pp.83-96.

Chappells et al. 2005. *Debating the future of comfort: environmental sustainability, energy consumption and the indoor environment*. Building Research & Information, 33(1), pp. 32-40.

Cohen et al. 1986. *Behavior, health, and environmental stress*. New York ; London : Plenum Press.

de Dear et al. 1997. *"Developing an Adaptive Model of Thermal Comfort and Preference." Final Report – ASHRAE RP-884*. Sydney: American Society of Heating, Refrigeration and Air-Conditioning Engineers, Inc. and Macquarie Research, Ltd.

de Dear et al. 1998. *Developing an adaptive model of thermal comfort and preference.* ASHRAE Transactions,104, pp.145-167.

de Dear et al. 2013. *Progress in thermal comfort research over the last twenty years*.

Indoor air,23(6), pp.442-61.

de Dear, R.J. & Leow, K. & Foo, S. 1991. ***Thermal comfort*** in the humid ***tropics***: Field experiments in ***air conditioned*** and naturally ventilated ***buildings*** in Singapore.

International Journal of Biometeorology, 34(4), pp.259-265.

Eliasson et al. 2007. *Climate and behaviour in a Nordic city.* Landscape and Urban Planning, 82(1), pp.72-84.

EN ISO 7730. 2005. *Ergonomics of the thermal environment - Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria (ISO 7730:2005)*. British Standards Institute.

Fanger et al. 1977. *Can colour and noise influence Man's thermal comfort?* Ergonomics, 20, pp.11-18.

Fanger, P.O. 1970. *Thermal comfort: analysis and applications in environmental engineering*. New York: McGraw-Hill.

Fanger, P.O. 1973. *Assessment of Man's Thermal Comfort in Practice.*

British Journal of Industrial Medicine, 30(4), pp.313-324.

Fanger, P.O & Toftum, J. 2002. *Extension of the PMV model to non-air- conditioned building in warm climates.* Energy and Buildings, 34(6), pp. 533-536.

Fountain, M. & Brager, G. & de Dear, R. 1996. ***Expectations of indoor climate control.***

Energy & Buildings, Vol.24(3), pp.179-182.

Gregory, R.L. 1970. *The intelligent eye*. London: Weidenfeld & Nicolson.

Healey et al. 2012. *Exploring the influence of qualitative factors on the thermal comfort of office occupants.* Architectural Science Review, 55(3), p.169-175.

Heijs et al. 1998. *Research on residential thermal comfort: some contributions from environmental psychology*. Journal of Environmental Psychology, 8(3), pp. 235-247.

Hirashima et al. 2016. *Daytime thermal comfort in urban spaces: A field study in Brazil.* Building and Environment,107, pp.245-253.

Holl et al. 2006. Questions of perception: phenomenology of architecture. New Ed.

San Francisco : William Stout.

Huebner et al. 2016. *Saving energy with light? Experimental studies assessing the impact of colour temperature on thermal comfort.* Energy Research & Social Science, 15, pp.45-57.

Humphreys et al. 2016. *Adaptive thermal comfort : foundations and analysis.* London ; New York : Routledge, Taylor & Francis Group.

Knapp, K. 2015. *A study of modifications to the geometry of an interior envelope and the effect on mean radiant temperature and occupant thermal comfort.*

Rensselaer Polytechnic Institute Troy, New York : ProQuest LLC.

Kobayashi et al. 1992. *Physiological responses to illuminance and color temperature of lighting*. The Annals of Physiological Anthropology, 11(1), pp.45–49.

Mangone et al. 2014. *Constructing thermal comfort: Investigating the effect of vegetation on indoor thermal comfort through a four season thermal comfort quasi-experiment.* Building and Environment. 81, pp.410-426.

Microsoft Corp. 2017. Load the Analysis ToolPak. [online] Retrieved from https://support.office.com/en-gb/article/Load-the-Analysis-ToolPak-6a63e598-cd6d-42e3-9317-6b40ba1a66b4?ui=en-US&rs=en-GB&ad=GB.

Mors et al. 2011. *Adaptive thermal comfort in primary school classrooms: Creating and validating PMV-based comfort charts*. Building and Environment, 46(12), pp. 2454-2461.

Nicol, J.F. & Humphreys M.A. 2002. *Adaptive thermal comfort and sustainable thermal standards for buildings.* Energy & Buildings, 34(6), pp.563-572.

Nikolopoulou et al. 1999. *Thermal comfort in urban spaces: Different forms of adaptation*. REBUILD International Conference: The Cities of Tomorrow, Barcelona, 4-6 October 1999.

Nikolopoulou et al. 2001. *Thermal comfort in outdoor urban spaces: Understanding the human parameter.* Solar Energy, 70(3), pp. 227-235.

Nikolopoulou, M. & Steemers, K. 2003. Thermal comfort and psychological adaptation as a guide for designing urban spaces. **Energy & Buildings, 35(1), pp.95-101.**

Ohta, H. et al. 2007. *Effects of redecoration of a hospital isolation room with natural materials on stress levels of denizens in cold season.* International Journal of Biometeorology, 52(5), pp.331-340.

Pallasmaa, J. 2005. ***The eyes of the skin*** : architecture and ***the*** senses.

Chichester : John Wiley.

Parsons, K. C. 2003. *Human thermal environments: the effects of hot, moderate, and cold environments on human health, comfort and performance.* 2ND Ed, London : Taylor & Francis.

Poppelreuter, T. 2012. *Sensation of Space and Modern Architecture: a psychology of architecture by Franz Löwitsch*. The Journal of Architecture, 17(2), pp.251-272.

Qin et al. 2014. *The effect of indoor plants on human comfort.* Indoor and Built Environment. 23(5), pp.709-723.

Rajapaksha, I. 2017. *Effect of spatial ambience on thermal adaptation in tropics: Case of free-running shared spaces in coastal hotels of Sri Lanka.* Procedia Engineering,180, pp.975-985.

Roessler, K. K. 2012. *Healthy Architecture! Can environments evoke emotional responses?* Global journal of health science, 4(4), pp. 83-89.

Rohles, et al. 1976. *INTERIOR DESIGN, COMFORT AND THERMAL SENSITIVITY*. Journal of Interior Design, 2(2), pp.36-44.

Rohles, F. 2007. *Temperature & Temperment: A Psychologist Looks at Comfort.* ASHRAE Journal, 49(2), pp.14-16,18,20,22.

Ritterfeld, U & Cupchik, G.C. 1996. *Perceptions of interior spaces*.

Journal of Environmental Psychology,16(4), pp.349-360.

Vine, E. L. 1986. *Saving Energy the Easy Way - an Analysis Of Thermostat Management*. Energy, 11(8), pp.811-820.

Willey, H.B. 1987. *Proceedings of the European Conference, Newcastle upon Tyne, UK, 15–17 September 1987.* pp. 305–316.

Wohlwill, J. 1974. *Human adaptation to levels of environmental stimulation.*